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Biomechanical analysis of walking: Effects of gait velocity and arm swing amplitude

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Abstract

Background and Purpose: *Human walking has been extensively studied by many investigators and numerous mathematical models of lower limb movements have been developed but few reports have been written about contribution of the upper limbs to the locomotion process. The aim of this study was to investigate the influence of walking speed and effect of the upper limb swing on the trajectory of the whole body mass center, as well as on ground reaction forces during human walking.*

Material and Methods*: An automatized method for determination of the whole body mass center has been established. Gait analysis was performed on 52 subjects using the Elite system and Kistler force platform. The recording of trajectories of characteristic body points on subjects and measurement of ground reaction forces were performed at normal speed walking with natural and emphasized rhythmic upper limb swing and at fast walking speed. The determined mean values of normalized components of trajectory of the body mass center and ground reaction forces were compared.*

Result and Conclusion: *The study showed that components of ground reaction forces and trajectory of the whole body center of mass are influenced by changes in arm swing and gait velocity. Maximum magnitudes of components of ground reaction force increased for normal speed walking with emphasized upper limb swing. The emphasized upper limb swing decreased the magnitude of vertical oscillations of the body center of mass and thus may influence energy expenditure.*

INTRODUCTION

Human walking is an extremely complex biomechanical process. A large number of investigations have been carried out in the field of human walking *(1, 2)*. Interest in the analysis of human walking arises from the fact that motion analysis yields information on underlying (possibly pathological) processes which are not directly observable except by using highly invasive techniques. The trajectory of the body center of mass is often a relevant parameter in studying human walking because it reflects the motion of the whole body. An alteration in the trajectory of the body mass center may indicate a clinical manifestation of an underlying pathology, or just a means of maintaining stability in gait *(3, 4)*. Since it reflects the whole body motion, the center of mass can provide useful parameters for the overall evaluation of walking and, in combination with other kinematic and kinetic data, give a more precise analysis, thus enabling practical application.

A great number of studies on human walking have been published and numerous mathematical models of analysis as well as simulations of human walking have been developed *(5–9)*. Because of the complexity of human body, these models are very simplified and they mostly study the movement of legs while the movement of upper limbs has been neglected *(10)*. This study intends to provide a better understanding of the contribution of the upper limbs to human gait. The aim of this study was to investigate the influence of walking speed and effect of upper limb swing on the trajectory of the whole body mass center, as well as on ground reaction forces during human walking.

MATERIALS AND METHODS

We established an automatized method for determining the whole body center of mass. The actual positions of the center of mass were calculated from full body kinematics using appropriate kinematic and anthropometric data. The first premise of this method is that the human body can be perceived as a system of rigid segments. The total body center of mass is defined by the following equation:

$$\vec{r}_{\mathrm{T}} = \frac{\sum_{i=1}^{n} m_{\mathrm{i}}\, \vec{r}_{\mathrm{i}}}{M} \tag{1}$$

where $\vec{r}_{\mathrm{T}}$ and $\vec{r}_{\mathrm{i}}$ represent the position vectors of the center of mass of the whole body and of the i-th segment, respectively, while M and m_{i} represent the mass of the total body and of the i-th segment, respectively.

The values of mass and center of mass for each segment were calculated using the regression method established by Donsky and Zatsiorsky *(11)*. 24 reflective markers were attached to palpable landmarks on human body. The landmarks allowed the definition of a 15-segment whole-body model which included the following segments: foot, lower leg, thigh, upper trunk (thorax and abdomen), lower trunk (pelvis), head and neck, upper arm, forearm and hand *(12)*. The markers were placed on the skin and it was necessary to approximate the joint centers and the centers of mass of each segment. The joint centers were used as reference points for estimating the positions of segment centers of mass. The centers of mass of the upper leg, lower leg, upper arm and forearm lie on the lines which connect the neighboring joint centers. The joint centers and the centers of mass of segments were approximated using the data from literature *(11–14)*.

A gait analysis was performed on 52 subjects (characteristics summarized in Table 1) with no apparent abnormalities of the locomotion system, using the Elite system with two CCD cameras and a Kistler force platform. A 9-m walkway, with the Kistler force platform located in the center, was used for gait analysis. An ample space at both ends of the walkway was available to allow subjects to walk at a nearly constant velocity. The subjects walked barefoot and they were asked to walk successively at what

TABLE 1

Personal profile of test subjects included in the study.

Gender	No. of subjects	Age, yrs.			Weight, N		
		$\bar{x}$	min.	max.	$\bar{x}$	min.	max.
Female	20	27.8	21	31	552	494	612
Male	32	30.5	22	26	829	710	1100

they felt to be their normal and fast speed. During the experiment each subject was instructed to walk 30 times: ten at normal walking speed, ten at fast walking speed and the remaining ten at normal walking speed with emphasized rhythmic upper limb swing. The emphasized upper limb swing meant a full reciprocal excursion of both arms. 3D coordinates of the marked points were the input data for a computer program which calculates the orientations of segments, joint centers, segment mass centers and trajectories of the whole body mass center during walking. For example, Figure 1 shows a model of a subject at normal speed walking with drawn calculated trajectory of the whole body center of mass.

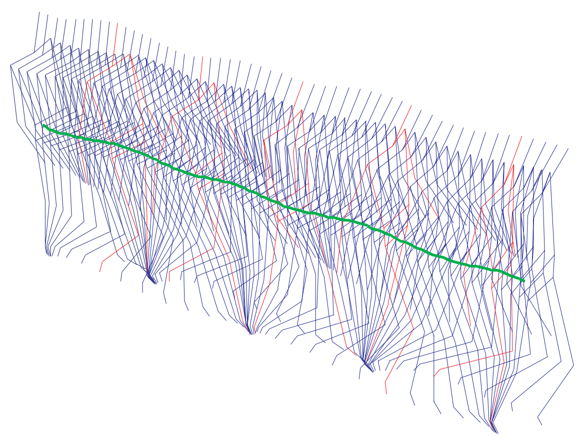

Figure 1. *Model of a subject during walking at normal speed with drawn calculated trajectory of the whole body center of mass.*

The recorded data were processed and the walking trials that had no contact of the entire foot with the Kistler force plate were rejected. In order to be able to compare the characteristics of walking, the determined characteristics of gait were normalized. The determined trajectories of the body center of mass were normalized by the subject's height to give displacements of the center of mass in percentages of the body height. The original data of the body center of mass displacement were averaged by normalizing them to one hundred sample points per one walking cycle through spline interpolation. The first and the last point marked the left heel contact. Ground reaction forces were normalized by body weight and shown as a function of the duration of contact between the foot and the force platform. The total duration of contact represents 100% on the time axis.

RESULTS

The range of normal gait speed was 0.95 m/s $\leq v \leq$ 1.7 m/s (mean speed 1.27 m/s, S.D. 0.12 m/s) and the range of fast gait speed was 1.7 m/s $\leq v \leq$ 2.4 m/s. (mean speed 1.96 m/s, S.D. 0.20 m/s). From *individual patterns* of walking characteristics, a *typical pattern* for every subject was determined to describe the inter-subject variation.

Typical patterns of the three components of ground reaction forces (vertical, fore-aft, medio-lateral), as well as *typical patterns* of the displacements of the body mass center in the lateral, vertical and fore-aft direction during a gait cycle, were established for every subject. Fore-aft axis represents a longitudinal axis lying on the line of progression. *General patterns* and a variation bandwidth of one standard deviation for a particular walking manner were determined from *typical patterns* of all subjects for the same manner of walking. A *general pattern* represents the mean curve of the entire group of subjects involved in the study.

Figure 2 shows a comparison of *general patterns* of three-dimensional displacements of body center of mass for walking at normal walking speed with natural and emphasized upper limb swing, and for walking at fast speed.

General patterns of displacements of the body center of mass for walking at normal speed with and without emphasized upper limb swing, and for walking at fast speed, are compared in Figure 2, and the maximum displacements of the body center of mass in the lateral, vertical and fore-aft directions are shown in Table 2.

With regard to walking at normal speed with the natural and the emphasized upper limb swing, the displacements of the body center of mass for the emphasized upper limb swing decreased in the lateral and vertical directions, and increased in the fore-aft direction. With regard to walking at normal and fast speed, the displacements of the body center of mass for fast speed walking decreased in the lateral and fore-aft direction, and slightly increased in the vertical direction.

Figure 3 represents a comparison of *general patterns* of the three components of ground reaction forces during walking at normal speed with the natural and emphasized upper limb swing and during walking at fast speed. A typical feature of the vertical force component is its »dual hump« shape. During walking at normal speed

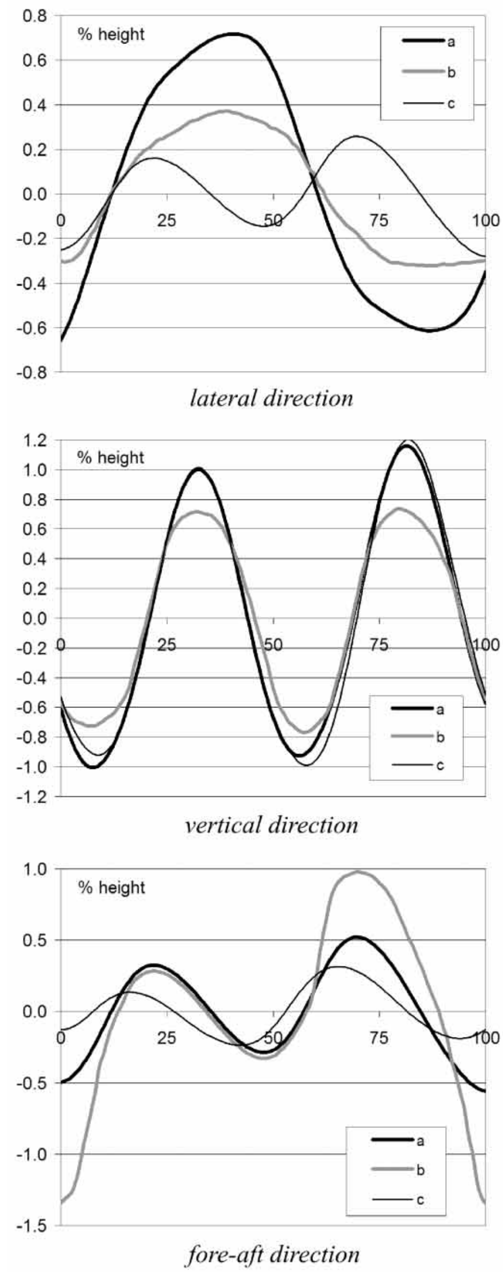

Figure 2. *Comparison of* general patterns *of normalized displacements of the body center of mass in lateral, vertical and fore-aft direction for normal speed walking (a), fast speed walking (c) and normal speed walking with emphasized upper limb swing (b).*

TABLE 2

Maximum displacements of *general patterns* of the body center of mass in lateral, vertical and fore-aft direction.

Direction	Maximum displacement in percentage of body height		
	Normal speed walking with natural upper limb swing	Normal speed walking with emphasized upper limb swing	Fast speed walking with natural upper limb swing
Lateral	1.34	0.70	0.53
Vertical	2.16	1.50	2.20
Fore-aft	1.07	2.30	0.56

with the natural upper limb swing, the second peak is higher when compared with the first one. During walking at fast speed and at normal speed with the emphasized upper limb swing, the first peak is higher. The maximum values of the first and the second peak of *general patterns* of vertical ground reaction forces are shown in Table 3.

The *general pattern* of the fore-aft component of ground reaction force at natural normal walking speed is nearly anti-symmetric with a larger fore and a smaller aft force. In walking at normal speed with the emphasized upper limb swing, the fore-force was slightly decreased and the aft-force was increased. With regard to walking at normal and fast speed, the fore and the aft force were increased during fast speed walking.

The *general pattern* of the medio-lateral component is asymmetric and the medial force is predominant. The medial force increased in walking at normal speed with the emphasized upper limb swing. In the condition of fast speed walking, one can note that the lateral force increased, but the medial force increased only in the first part of the duration of contact and then decreased.

CONCLUSION

The study showed that gait patterns were influenced by changes in arm swing and in gait velocity. An alternation in the normal motion of upper limbs results in changes in the whole body kinematics and in dynamic stability.

The measurements performed showed that components of ground reaction forces were influenced by changes in the upper limb swing during walking. The maximum magnitudes of vertical components of the ground reaction force, aft-force and medial force increased for normal speed walking with the emphasized upper limb swing.

In the vertical direction, the center of mass for normal and fast speed walking describes a smooth regular sinusoidal curve with two cycles for every gait cycle; i.e. the center of mass is displaced in the vertical direction twice during gait cycle. In the lateral direction, the center of mass for normal speed walking is displaced to the right and to the left, in association with the support of the weight-bearing extremity. For fast speed walking, the center of mass is displaced in lateral direction twice during a gait cycle.

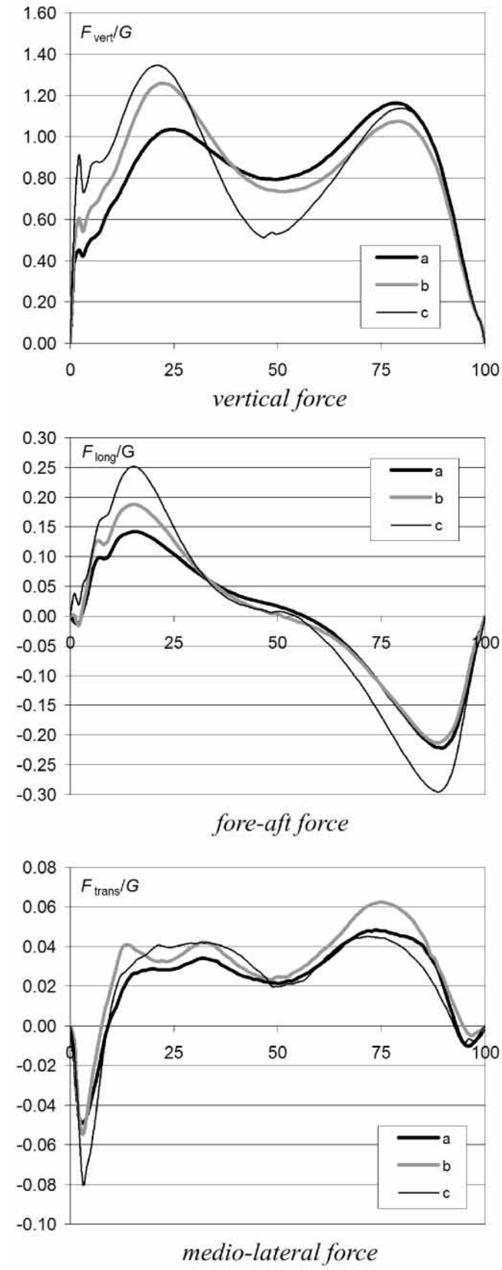

Figure 3. *Comparison of general patterns of the three components of ground reaction forces during walking at normal speed with natural (a) and emphasized upper limb swing (b) and during walking at fast speed (c).*

TABLE 3

The maximum values of the first and second peak of general patterns of vertical ground reaction forces. F_{vert}/G represents vertical ground reaction force normalized by body weight.

	Normal speed walking with natural upper limb swing	Normal speed walking with emphasized upper limb swing	Fast speed walking with natural upper limb swing
$(F_{vert}/G)_{max,I}$	1.04	1.26	1.34
$(F_{vert}/G)_{max,II}$	1.16	1.08	1.14

With regard to normal and fast speed walking, the displacements of the body center of mass for fast speed walking decrease in the lateral and fore-aft direction.

With regard to walking with the natural and emphasized upper limb swing, the displacements of the body center of mass for the emphasized upper limb swing decrease in the lateral and vertical directions and increase in the fore-aft direction. We may conclude that the trajectory of the body center of mass in walking with emphasized upper limb swing tends to exhibit decreased curvature and come close to a straight line.

The arms decrease the magnitude of vertical oscillations of the body center of mass during walking and thus may influence energy expenditure.

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